1st AND 2nd STEP CHARACTERISTICS PROCEEDING THE SPRINT START IN AMPUTEE SPRINTING

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The aim of this study was to investigate 1st and 2nd stance phase spatio-temporal and ground reaction force (GRF) parameters of four unilateral transtibial amputee (AMP) and nine able-bodied (AB) sprinters. Data were collected using a 3D motion capture system (Vicon, 250 Hz) and two force plates (Kistler 1000 Hz). Aside from flight time (d=0.32) and step width (d=0.60), all spatio-temporal parameters were significantly lower for the AMP compared to the AB athletes for both limbs. Peak horizontal GRF and relative impulse were significantly decreased for the AMP group, while the peak vertical GRFs were significantly decreased for the 1st (affected limb) but increased for the 2nd step (intact limb), with the relative vertical impulse data being similar. Therefore running prostheses appear to limit the performance of AMP compared with AB sprinters.

KEY WORDS: sprint start, prosthesis, performance diagnostics

INTRODUCTION: The ability to quickly generate a high sprinting velocity from a static position in the starting blocks is crucial in sprint running. The start performance including the first steps compromises in able-bodied elite athletes approximately 5% of the total 100m race time (Harland & Steele, 1997). Optimal starting performance is characterized by a successful push off the starting blocks and the ability to generate high horizontal centre of mass (COM) acceleration with the steps following block clearance (Willwacher, 2015). The following first step shows the greatest increase in velocity (Salo, Keränen, & Viitasalo, 2005) and it has been demonstrated that faster sprinters produce a higher net propulsive impulse during the first stance phase due to a greater rate of external force development (Bezodis, Salo, & Trewartha, 2014). Additionally COM acceleration can be generated due to different performance characteristics of the knee and ankle joint compared to the maximum velocity phase. During the first stance phase the ankle joint generates 3.3-4.0 times more energy than it absorbs, while at maximum velocity the amount generated is beneath the amount absorbed (0.6 fold) (Bezodis, Kerwin, & Salo, 2008; Bezodis et al., 2014). Unlike in the maximum velocity phase, during first stance phase the knee does not need to reverse negative vertical velocity and therefore plays a greater role as an energy generator. In able-bodied athletes the source to generate positive power are the contractile elements of the extensor muscle-tendon units (Winter, 2009). Athletes with lower extremity amputation are lacking some of these contractile elements and hence are less able to accelerate quickly out of the blocks. Additionally in this phase lower extremity amputee athletes cannot rely on the energy storage and release cycle of their running specific prostheses (RSP) as very little vertical energy is brought into the RSP in this phase of the race. Willwacher, Herrmann, Heinrich, Funken, Potthast, Bezodis et al. (2015) compared the starting block performance of 3 transfemoral and 4 transtibial sprinters to a performance matched able-bodied group of 34 male and female sprinters. These authors identified, that the amputee participants demonstrated significantly increased block times, decreased rear block forces (with the prosthetic limb) and a more vertical push off direction. The majority of the unilateral lower limb amputee athletes prefer to place the affected limb in the rear block and the intact limb in the front block (Taboga, Grabowski, di Prampero, & Kram, 2014), hence the first contact is realized with the affected limb. Given the importance of the ankle and knee for the first step, of which one or both are missing in amputee athletes, adaptive mechanisms when starting in a crouched position from the starting blocks will need to be used. It yet remains unclear, whether the intact limb of the unilateral transtibial amputees displays a movement pattern comparable to an able-bodied group, or if it also displays adaptive mechanism that possibly compensate for the affected limb. It is hypothesised, that lower limb amputee sprinters will demonstrate altered spatio-temporal and kinetic performance variables in both the affected and the intact limb compared to able-bodied sprinters.

METHODS: Nine elite able-bodied (AB) sprinters (21.9 ± 4.5 yrs, 1.78 ± 0.04 m, 76.4 ± 3.1 kg, 10.10-10.96s 100-m personal best times) and 3 elite and 1 national level transtibial amputee sprinters (AMP) (26.0 ± 4.8 yrs, 1.91 ± 0.11 m, 80.9 ± 7.6 kg, 11.70-12.40 s 100-m personal best times) participated in this study. The performance of the AB and AMP group was 9.6 ± 3.7% and 13.8 ± 3.0% slower than the current 100m sprint world record of each group, respectively. The data collection took place at the indoor tracks of the Cardiff Metropolitan University (n= 9 AB, 2 AMP) and the German Sport University (n= 2 AMP). Both indoor tracks were equipped with a 3D motion capture system (VICON, Oxford Metrics Ltd, UK) and at least two force plates to capture first and second stance (Kistler Instruments Corporation, Winterthur, Switzerland). Kinematic data were collected at 250 Hz and kinetic data at 1000 Hz. The same start block system was used (Willwacher, Hermann, Heinrich, & Brueggemann, 2013) including speed gates at 5 m and 10 m. Athletes performed an individual warm-up and were then asked to conduct 3-5 maximum effort 10 m acceleration runs from the blocks, touching the force plates with 1st and 2nd step respectively. Three successful trials for each condition were collected and the mean of these trials was taken for further analysis. As "toe"-markers, reflective markers were placed at the 2nd metatarsal joint at the intact limbs and at the medial and lateral distal part of the RSP. A virtual toe marker was then created half-way between these two markers. Data were analyzed for the 1st and 2nd stance phase and the respective flight phase in between. The kinetic data were used to identify stance and swing phases, and the toe markers were used to identify step length and step width. Step frequency of the first step was calculated by 1/(1st stance contact time+flight time) and step velocity was calculated as the product of step frequency and step length. Ground reaction force (GRF) data were filtered using a lowpass 4th order butterworth filter of 25 Hz and normalized to body weight. Horizontal and vertical impulse, obtained by integrating (trapezium rule) the respective force-time signal (with bodyweight subtracted from the vertical force signal) was divided by body mass to calculate the change in horizontal and vertical velocity. Due to the low sample size in the transtibial amputee group, statistics were calculated using the Mann-Whitney U-test for independent samples with a significance level of 5%. Effect sizes were calculated using Cohen's d (Cohen, 1992) with effect sizes being small for $d < 0.40$, medium between 0.40–0.79 and high with effect size $d \geq 0.80$.

RESULTS and DISCUSSION: All transtibial amputee athletes started with the affected leg in the rear block position and hence conducted the first stance phase with the affected leg. Aside from flight time (p= 0.164, d=0.32) and step width (p = 0.44, d=0.60), all other spatio-temporal parameters were significantly lower for the transtibial amputee athletes with effect sizes above 1.65 (Table 1). Most spatio-temporal parameters refer to the ground contact of the affected limb and the subsequent flight phase, and clearly demonstrate performance deficits in comparison to the able-bodied counterparts. Interestingly second step contact time was also significantly longer in the AMP group, although this occurred with the intact limb. This may be explained by the AMP sprinters having to invest more time on the ground during second stance to increase horizontal velocity given their significantly reduced ability to generate horizontal impulse with the affected limb (Table 2). The main function of the first steps out of the block is to generate a high horizontal velocity and a high net propulsive impulse (Bezodis et al., 2014; Salo et al., 2005) (Table 2). In able-bodied athletes the horizontal impulse is expected to decrease with each step (Salo et al., 2005).

Table 1
Spatio-temporal parameters for 1st and 2nd ground contact (mean ± SD) and statistical comparison between AB and AMP athletes

	AB	AMP	Sig.	ES (d)
5 m [s]	1.26 ± 0.04	1.63 ± 0.14	.005*	3.72
10 m [s]	1.92 ± 0.03	2.43 ± 0.18	.005*	4.03
contact time - 1st step [s]	0.19 ± 0.02	0.27 ± 0.04	.009*	2.49
contact time - 2nd step [s]	0.16 ± 0.01	0.20 ± 0.03	.005*	1.65
flight time [s]	0.06 ± 0.01	0.05 ± 0.02	.164	0.32
step length [m]	1.14 ± 0.09	0.85 ± 0.10	.005*	3.04
step width [m]	0.28 ± 0.06	0.37 ± 0.19	.440	0.60
step frequency -1st step [Hz]	4.04 ± 0.39	3.18 ± 0.53	.020*	1.85
velocity -1st step [m/s]	4.57 ± 0.26	2.67 ± 0.31	.005*	6.72

AB: able-bodied, AMP: amputees, sig: * indicates significant difference, ES: effect size, d: Cohen's d

Transtibial amputee athletes demonstrated significantly lower maximum horizontal forces with the 1st stance phase being applied by the affected limb (p=0.005, d=9.52) as well as with the intact limb at the 2nd stance phase (p=0.005, d=1.89). The relative horizontal impulse which indicates the change of horizontal velocity being developed with the respective ground contact reflects these values and demonstrates significantly decreased relative impulses for both stance phases compared with the AB group (p=0.005, d=3.51 and p=0.021, d=1.28). Relative horizontal impulse decreased in both groups between first and second contact as expected, however able-bodied athletes realized a 26% decrease, while the TT amputee athletes realized a notable lower decrease of 16% from first to second step (Table 2).

Table 2
Kinetic parameters for 1st and 2nd ground contact (mean ± SD) and statistical comparison between AB and AMP athletes

	1st contact				2nd contact			
	AB	AMP	sig.	ES (d)	AB	AMP	sig.	ES (d)
peak horizontal GRF [N/BW]	1.11 ± 0.04	0.59 ± 0.07	.005*	9.52	0.96 ± 0.03	0.67 ± 0.21	.005*	1.89
peak vertical GRF [N/BW]	2.09 ± 0.07	1.88 ± 0.17	.020*	1.62	1.98 ± 0.10	2.32 ± 0.25	.009*	1.77
rel. horizontal impulse [m/s]	1.22 ± 0.10	0.83 ± 0.13	.005*	3.51	0.90± 0.07	0.70 ± 0.21	.021*	1.28
rel. vertical impulse [m/s]	0.61 ± 0.16	0.35 ± 0.36	.123	0.94	0.49 ± 0.13	0.69 ± 0.30	.089	0.84

AB: able-bodied, AMP: amputees, sig: * indicates significant difference, ES: effect size, d: Cohen's d

During the acceleration phase athletes must not only generate horizontal velocity, but also transfer their body position from a crouched position at the start into an upright sprinting position, hence they have to produce vertical GRF to raise their COM. While able-bodied athletes generated significantly higher peak vertical GRF with the first step (p=0.030, d=1.62) compared to their transtibial amputee counterparts, their peak vertical GRF forces were significantly lower for the second step (p=0.009, d=1.77). This can be attributed to the mechanical characteristics of the RSP. With the first step it is hardly possible to vertically compress the RSP and provoke a release of vertical energy, hence the athlete's ability to transfer to an upright position is limited and it seems that athletes cannot adequately compensate this task with the remaining knee and hip muscles of the affected limb. It appears that the intact limb compensates for this deficiency by producing significantly higher peak vertical GRF with the second step. Surprisingly, the change of vertical velocity data did not reveal statistically significant differences. Possibly, the prolonged contact time at the first step supports the AMP athlete to realize a change of vertical velocity being somewhat similar to the able-bodied counterparts. However effect sizes of d=0.95 (ground contact 1) and d=0.84 (ground contact 2) indicate a tendency towards a decreased change of vertical velocity being realized with the RSP and increased change of vertical velocity being realized with the intact limb at the second ground contact.

CONCLUSION:

The findings of this study indicate that unilateral transtibial amputee sprinters have reduced performance indicators in the early acceleration phase in the affected limb compared to their able-bodied counterparts. Additionally, the intact limb of the transtibial amputee sprinters cannot compensate for the lower performance of the affected limb and shows lower performance indicators than the respective limb of able-bodied participants. Therefore, it is concluded that the characteristics of the RSP do not support the sprinter equally as an intact limb in the early acceleration phase, in which the generation of horizontal velocity is the main goal. In contrast to the maximum velocity phase, at which the characteristics of the RSP can be ideally used by the AMP athlete (Brueggemann, Arampatzis, Emrich, & Potthast, 2008), this study demonstrates that at the start and early acceleration the RSP does not replicate an intact limb. Whether this is a net disadvantage over a complete race yet needs to be investigated.

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